TERAHERTZ RADIATION GENERATION DURING LASER- PLASMA INTERACTION IN THE PRESENCE OF WIGGLER MAGNETIC FIELD

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In partial fulfillment of the Requirements for the

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Under the guidance

of

Dr. Niti Kant

Phagwara, Punjab

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DECLARATION

I hereby declare that the dissertation report entitled, "Terahertz radiation generation during laser plasma interaction in the presence of wiggler magnetic field" submitted for M.Sc. (Hons.) Physics degree is entirely my original work and all ideas and references have been duly acknowledged. It does not contain any work for the award of any other degree or diploma at any other university.

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<u>CERTIFICATE</u>

This is to certify that **Miss. Shivani** has completed the dissertation report entitled "**TERAHERTZ RADIATION GENERATION DURING LASER PLASMA INTERACTION IN THE PRESENCE OF WIGGLER MAGNETIC FIELD**" under my guidance and supervision. To the best of my knowledge, the present work is the result of her original investigation and study. No part of the dissertation been submitted for any other degree of diploma.

The dissertation is fit for the submission for the partial fulfillment of the condition for the award of M.Sc. Honors in Physics

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ABSTRACT

The THz radiations are generated during laser plasma interaction in the presence of wiggler magnetic field. The lasers transmit diagonally through the hot plasma and because of the effect of the ponderomotive force nonlinearity in the medium arises. THz radiations are emitted in the reflection direction. The efficiency of the reflected THz radiations increases with the wiggler magnetic field. Angle of incidence of lasers is an important parameter for efficient THz radiation. Optimization of laser and plasma parameters has been done for better efficiency.

CONTENTS

CHAPTER-1

INTRODUCTION

Terahertz radiation – additionally called sub metric linear unit radiation, rate waves, high frequency T-rays, T-waves, T-light, T-lux or terahertz – consists of magnetic attraction waves frequencies from 0.3 THz (one terahertz $=10^{12}$ Hz). As a result of rate radiation begins at a wavelength of 1mm and takings into shorter wavelengths, it's typically called the sub metric linear unit band. Rate radiation lies between infrared and microwave regions within the spectrum called rate gap. These radiations generated by interaction of short pulse extremely energetic non particulate radiation with plasma. Plasma is employed as a medium as a result of it will give terribly high moment and might simply handle very high power radiations. In many experiments plasma is utilized as a nonlinear medium for the terahertz generation.

The spectrum of THz radiation was associated in unknown region for an extended time because of the shortage of economical sources and detectors. However, within the previous few decades, researchers have found nice interest in developing dynamical and economical terahertz sources owing to their various applications in semiconductor and high-temperature superconductor characterization, label-free genetic analysis, cellular level imaging, biological sensing and, tomographic imaging, explosives detection and chemical analysis . Interaction of short optical device pulses with plasma is an energetic space of analysis because of the potential applications like optical device wake field accelerators, with harmonic generation, advancement optical device fusion schemes and because of the non-ionizing nature and also the ability to penetrate many millimeters, terahertz radiation is appropriate for material characterization and diagnosing of cancerous cells. The subject of terahertz radiation generations has been attracting continuous interest with made implications in each elementary and applied sciences. Terahertz radiation sources have variety of applications in biological imaging, surface chemistry, and high-field condensed-matter studies. Numbers of processes are adapted to generate terahertz radiation. A significant challenge that stops the complete exploitation of the terahertz is that the lack of cheap, compact and dynamical or high-efficiency terahertz generators. For the developments of novel and sensible terahertz sources, several schemes have emerged by irradiating plasmas with short pulse lasers.

In this paper, we use the external wiggler magnetic field to enhance the efficiency of the reflected THz radiation. To increase the yield we couple THz wave with the plasma wave. Variation of normalized THz amplitude with plasma frequency and angle of incidence for different values of normalized wiggler magnetic field has been discussed. Simulation results are plotted and discussed.

CHAPTER-2

REVIEW OF LITERATURE

Kumar et al. [1] performed the experiment in which they used two lasers that passes through the hot plasma. The passed the laser through the surface diagonally. The ponder motive force exists and non-linearity appears. The THz radiations emits only in single direction. The production was increased when they coupled with Langmuir wave.

Yuan et al. [2] performed an experiment during which high THz radiation was made having intensity ($\sim 7\times W/cm^2$). Once they heat up the target an intense pulse of optical maser accelerated protons. They determined that the extent of THz emission reduces by preheating & growth of target. The full energy of the THz radiation is found to decrease as compared to cold target reference. Due to the advancement of technology and numerous applications within the field of spectrum analysis, radical broadband THz detection and to finding out the ionization technology, Jiayu Zho et al. [3] determined that strong superluminal propagating THz pulse in air is generated. In their experiment they studied that time unit optical maser could be operated of the length of the filament and THz pulse is radio-controlled on that filament. They used the Gaussian shift having diameter 1cm.

Dai and Zhang [4] studied that by the utilization of the part compensator for the generation of intense THz waves that has high potency from optical maser induced plasma with excitation by time unit pulses at each 800nm(ω) and 400nm(2ω). They determined the experiment with unit of time part compensator that has potential applications for remote sensing and identification and conjointly for coherent management of plasma formation and high harmonic generation in gas plasma.

Due to the wide applications of the terahertz radiation, Kumar et al. [5] performed the experiment at Pohang Accelerator Laboratory and studied that by victimization density modulation of relativistic electromagnetic wave, an information measure of radiation was inflated over five terahertz. For generating radical intense radiation they used radical short lepton bunch of the order of unit of time. They used chicane to convert the energy modulation of lepton bunch to the density modulation. They terminated that optical maser power, beam of light waist size and chicane play a crucial role to more improve the amplitude of the terahertz radiation.

Bhasin and Tripathi [6] discovered that THz amplitude inflated by thirty times when field of force was applied by 60 KV/cm. The magnitude of THz amplitude to it of filament amplitude is ~ at optical maser intensities. Owing to the dc field of force, coupling is inflated. They conjointly showed that the THz amplitude inflated with the THz frequency.

Jha and Verma [7] had given a 1 dimensional numerical model for learning the THz radiation generation by intense optical maser pulse propagating, within the extraordinary mode through attractable plasma. Further, 2-D PIC simulations victimization XOOPIC codes are performed to verify and compare the numerically foreseen results. The results obtained via simulation study are nearly as similar as those obtained from the 1-D numerical model, resulting in the verification of numerically obtained results. Transmission of the Wake fields through the plasma vacuum boundary has conjointly been investigated by simulation study.

Singh and Sharma [8] studied however electrons get including rippled density owing to the existence of a reflect driver once rate generates by the cross focusing of 2 linear optical maser beams. Owing to the periodic rate of the electrons lasers get including the density ripple, then the crosswise current created and rate radiation generates having frequency up to the plasma frequency. By victimization this methodology several parameters of lasers and plasmas were developed. For this they got a high potency of rate radiations of the order of$\sim$8.

Varshnety et al. [9] planned that by beating 2 extraordinary lasers with magnetized plasma with rippled density steady rate radiations generated. Magnetized rippled density plasma will resonantly excite rate waves by the beating of 2 x-mode lasers of frequencies in higher hybrid vary once the cyclist of ripples satisfies the specified section matching conditions. The specified ripple frequency for rate radiation generation will increase because the flux will increase and reduces because the rate frequency will increase. Thus, THz radiation frequency may be simply tuned by variable plasma density and applied flux. With the improvement of those parameters, the potency is achieved of the maximum order.

Varshnety et al. [10] performed an experiment within which they studied the dynamics of generation of THz wave by the beating of 2 optical maser beams within the presence of static force field, once solely reflect motive nonlinearity is operative. The coupling is more increased by the presence of static force field and spatial-Gaussian nature of optical maser beams. A rise of six-fold within the normalized amplitude of THz is discovered by applying an immediate current field of regarding fifty potential unit. Effects of frequency, ray dimension, and cyclist issue of modulated optical maser amplitude square measure studied for the economical THz radiation generation. These results may be used for generating controlled tunable THz sources for medical applications victimization low filament intensities ($\sim 10 W/cm^2$) of beating lasers.

Varshney et al. [11] ascertained that Dynamics of terahertz radiation generation by beating of 2 x-mode optical device beams in rippled attractable plasma is studied, once solely excogitate motive nonlinearity is operative. Triangular enwrap of x-mode optical device beams is used to boost beat excogitate driver engaged on plasma electrons. The additional momentum needed to excite terahertz wave resonantly by beating of 2 x-mode lasers of frequencies in higher hybrid vary is provided by the regularity of density ripples. The desired ripple frequency depends upon terahertz frequency and applied field of force. It decreases because the terahertz frequency will increase and will increase because the field of force will increase. Thus, frequency of terahertz radiation may be simply tuned by variable plasma density and applied field of force.

Hematizadeh et al. [12] projected a theme of THz radiation generation that by beating a 2 spatial-triangular optical device beams during a plasma with a spatially periodic density once electron-neutron collisions have taken into consideration. During this method, the optical device beams exert a excogitate driver on the electrons of the plasma and impart the periodic rate at the distinction frequency within the presence of a static field of force that is applied parallel to the direction of the lasers. They showed that higher potency and stronger terahertz radiation achieved when the parallel field of force is employed to match the perpendicular field of force. The results of beam dimension of lasers, collision frequency, regularity of density ripples, and field of force strength were analyzed for terahertz radiation generation. The terahertz field of the emitted radiations is found to be sensitive to collision frequency and field of force strength. During this theme with the improvement of plasma parameters, good potency was achieved.

Varshney et al. [13] suggested an experiment for THz radiation generation by photo-mixing of 2 super Gaussian optical device beams having totally different frequencies and wave numbers by applying dc field of force. The potency, power, beam quality, and tenability of the current theme exhibit high dependency upon the applied dc field of force at the side of q-indices and beam dimension parameters of super Gaussian lasers. Within this scheme, potency is achieved with the improvement of these parameters.

Singh et al. [14] projected a theme to attain terahertz radiation by the beating of cosh-Gaussian lasers in spatially periodic density plasma (ripple density). They showed that the lasers exert a nonlinear force that gives periodic rate to electrons that further couples with the density ripple to get a stronger transient current attributable to the special variation of their fields, driving terahertz radiation. The importance of laser-beam dimension parameters, decentered parameter, amplitude and regularity of the density structure measured for terahertz emission. By dynamical the decentered parameter the height intensity of lasers may be shifted to the direction and a notable modification is found within the magnitude of terahertz field amplitude and its conversion potency.

Cho et al. [15] projected a replacement mechanism for magnetic force emission within the THz (THz) frequency regime from optical device plasma interactions is represented. A localized and long-lived thwart wise current is created by 2 counter-propagating short optical device pulses in infirm attractable plasma. They showed that the electromagnetic radiation divergent from this current supply, although its frequency is near cut-off of the close plasma, grows and diffuses towards the plasma-vacuum boundary, emitting a powerful monochromatic terahertz wave.

Gishini et al. [16] generated terahertz radiation through the interaction of laser pulses having time period is in ultra short range with the molecular hydrogen plasma. They used a two dimensional particle in Cell- Monte Carlo Collision simulation scheme to examine the generation of THz. They used high power femtosecond laser having intensity $10^{17} W/CM^2$ with a Gaussian pulse.

Miao and Antonson [17] examined for non-linear excitation of plasma waves and laser pulse depletion, THz radiations were developed in corrugated plasma channels. For this they developed various theoretical analysis and full format PIC simulations. For obtaining the maximum conversion efficiency THz energy to optical pulse energy they used various structures of plasma channel and parameters of the laser pulses.

Bakhtiari et al. [18] used two Gaussian laser array beams. They have interacted Gaussian laser array beams with the plasma which is electron-neutral collisional plasma and based on this scheme they generate THz radiation. The efficiency of THz radiation using this method increases if use one Gaussian laser beam. By using this method the efficiency of the THz radiation is 0.07% which is three times greater than the efficiency obtained by using single Gaussian laser beam.

Ding and Shang [19] proposed a method in which they used femtosecond laser and thin solid target, then interacts and they got highly intense and high peak power THz radiation. The THz radiations are examined by PIC simulations. They told that for hot electron transport these THz radiations are very useful.

CHAPTER-3

THz RADIATION GENERATION

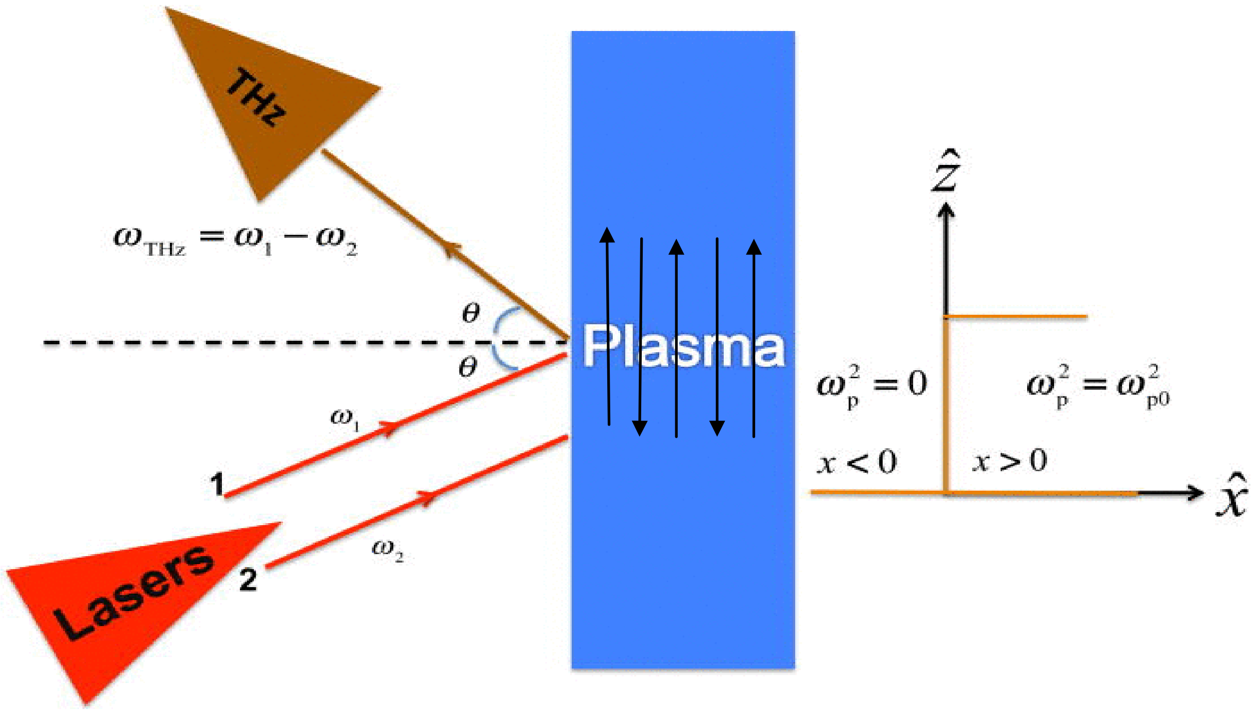

FIG. 1. Diagram for the THz radiation generation in hot plasma under wiggler magnetic field: Lasers incident diagonally on plasma and on the reflection side at angle of reflection equal to angle of incidence THz radiation evolving.

To explain the physics of electrostatic-electromagnetic wave coupling, we consider hot plasma of electron temperature Te with step density profile.

$$\omega_p^2 = \omega_{po}^2 \qquad \text{for } x>0$$

$$= 0 \qquad \text{for } x<0 \qquad (1)$$

Where ω_p is the plasma frequency.

Two p- polarized lasers of frequency ω_1 and ω_2 , are diagonally incident on the surface of plasma at x=0, at an angle of incidence θ. The laser fields inside the plasma are

$$\vec{E}_j = (\hat{z} - \hat{x}\tan\theta)\cos\theta A_j e^{-i(\omega_j t - k_j(z\sin\theta + \cos\theta))} \qquad (2)$$

$$\vec{B}_j = c(\vec{k}_j \times \vec{E}_j)/\omega_j \qquad (3)$$

Where j=1, 2, $\vec{k}_j = \omega_j / c$.

The applied wiggler magnetic field is

$$\vec{B} = B_0 e^{-ik_o z}\hat{y} \qquad (4)$$

The lasers convey oscillatory velocities to electrons, $\vec{v}_j = e\vec{E}_j / mi\omega_j$ and exerts a ponder motive force on electrons

$$\vec{F}_{p\omega} = -\frac{e}{2c}(\vec{v}_1 \times \vec{B}_2{}^* + \vec{v}^*{}_2 \times \vec{B}_1 + \vec{v}_1 \times \vec{B} + \vec{v}_2 \times \vec{B})$$

Use equation no. (3) & (4).

$$= -\frac{e}{2c}\left[\frac{e\vec{E}_1}{mi\omega_1} \times \frac{c(\vec{k}_2 \times \vec{E}_2{}^*)}{\omega_2} + \frac{e\vec{E}_2{}^*}{m(-i)\omega_2} \times \frac{c(\vec{k}_1 \times \vec{E}_1)}{\omega_1} + \frac{e\vec{E}_1}{mi\omega_1} \times B_0 e^{-ik_0 z}\hat{y} + \frac{e\vec{E}_2}{mi\omega_2} \times B_0 e^{-ik_0 z}\hat{y}\right]$$

$$= -\frac{e^2}{2mi\omega_1\omega_2}\left[\vec{E}_1 \times (\vec{k}_2 \times \vec{E}_2{}^*) - \vec{E}_2{}^* \times (\vec{k}_1 \times \vec{E}_2)\right] - \frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1 \times B_0 e^{-ik_0 z}\hat{y} + \vec{E}_2 \times B_0 e^{-ik_o z}\hat{y}\right]$$

Use

$\vec{a}\times(\vec{b}\times\vec{c})=b(a.c)-c(a.b)$

$$=-\frac{e^2}{2mi\omega_1\omega_2}\left[\vec{k}_2(\vec{E}_1..\vec{E}_2{}^*)-\vec{E}_2{}^*(\vec{E}_1.\vec{K}_2)-\vec{k}_1(\vec{E}_2{}^*..\vec{E}_1)-\vec{E}_1(\vec{E}_2{}^*.\vec{k}_1)\right]-\frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1\times B_0e^{-ik_0z}\hat{y}\right]-\frac{e^2}{2mi\omega_2 c}\left[\vec{E}_2\times B_0e^{-ik_0z}\hat{y}\right]$$

As $\vec{E}_1$ & $\vec{k}_2$ both are perpendicular to each other so that $\vec{E}_1..\vec{k}_2=0$

Similarly $\vec{E}_2{}^*..\vec{k}_1=0$, then equation becomes

$$\vec{F}_{pw}=\frac{-e^2}{2mi\omega_1\omega_2}\left[\vec{k}_2(\vec{E}_1..\vec{E}_2{}^*)-\vec{k}_1(\vec{E}_2{}^*..\vec{E}_1)\right]-\frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1\times B_0e^{-ik_0z}\hat{y}\right]-\frac{e^2}{2mi\omega_2 c}\left[\vec{E}_2\times B_0e^{-ik_0z}\hat{y}\right]$$

Use $\vec{E}_1.\vec{E}_2{}^*=\vec{E}_2{}^*.\vec{E}_1$ in above equation then we get

$$\vec{F}_{pw}=\frac{-e^2}{2mi\omega_1\omega_2}\left[\vec{k}_2(\vec{E}_1..\vec{E}_2{}^*)-\vec{k}_1(\vec{E}_1..\vec{E}_2{}^*)\right]-\frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1\times B_0e^{-ik_0z}\hat{y}\right]-\frac{e^2}{2mi\omega_2 c}\left[\vec{E}_2\times B_0e^{-ik_0z}\hat{y}\right]$$

$$\vec{F}_{pw}=\frac{-e^2}{2mi\omega_1\omega_2}\left[(\vec{k}_2-\vec{k}_1)\vec{E}_1..\vec{E}_2{}^*\right]-\frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1\times B_0e^{-ik_0z}\hat{y}\right]-\frac{e^2}{2mi\omega_2 c}\left[\vec{E}_2\times B_0e^{-ik_0z}\hat{y}\right]$$

$$\vec{F}_{pw}=\frac{e^2(\vec{k}_1-\vec{k}_2)}{2mi\omega_1\omega_2}\vec{E}_1.\vec{E}_2{}^*-\frac{e^2}{2mi\omega_1 c}\left[\vec{E}_1\times B_0e^{-ik_0z}\hat{y}\right]-\frac{e^2}{2mi\omega_2 c}\left[\vec{E}_2\times B_0e^{-ik_0z}\hat{y}\right]$$

Use all the values of $\vec{E}_1,\vec{E}_2$ in $\vec{F}_{pw}$

$$\vec{F}_{pw}=\frac{e^2(\vec{k}_1-\vec{k}_2)}{2mi\omega_1\omega_2}\vec{E}_1.\vec{E}_2{}^*-\frac{e^2}{2mi\omega_1 c}\left[(\hat{z}-\hat{x}\tan\theta)\cos\theta A_1e^{-i(\omega_1t-k_1(z\sin\theta+x\cos\theta))}\times B_0e^{-ik_0z}\hat{y}\right]$$

$$-\frac{e^2}{2mi\omega_2 c}\left[(\hat{z}-\hat{x}\tan\theta)\cos\theta A_2e^{-i(\omega_2t-k_2(z\sin\theta+x\cos\theta))}\times B_0e^{-ik_0z}\hat{y}\right]$$

$$\vec{F}_{pw} = \frac{e^2(\vec{k}_1 - \vec{k}_2)}{2mi\omega_1\omega_2}\vec{E}_1.\vec{E}_2{}^* + \frac{e^2}{2mic}B_0\cos\theta(\hat{x} + \hat{z}\tan\theta)e^{-ik_0z}$$
$$\times\left[\frac{A_1}{\omega_1}e^{-i(\omega_1 t - k_1(z\sin\theta + x\cos\theta))} + \frac{A_2}{\omega_2}e^{-i(\omega_2 t - k_2(z\sin\theta + x\cos\theta))}\right] \tag{5}$$

Where $\omega = \omega_1 - \omega_2$, -e is the electron charge and m is the rest mass. The ponder motive force convey oscillatory velocity to electrons, which is given below

$$\vec{v}_{\omega}^{NL} = -\frac{\vec{F}_p}{mi\omega}$$

Use equation no (5) we get

$$\vec{v}_{w}^{NL} = -\frac{e^2(\vec{k}_1 - \vec{k}_2)}{2mi^2\omega\omega_1\omega_2}\vec{E}_1..\vec{E}_2{}^* - \frac{e^2}{2m^2i^2\omega c}B_0\cos\theta(\hat{x} + \hat{z}\tan\theta)e^{-ik_0z}$$
$$\times\left[\frac{A_1}{\omega_1}e^{-i(\omega_1 t - k_1(z\sin\theta + x\cos\theta))} + \frac{A_2}{\omega_2}e^{-i(\omega_2 t - k_2(z\sin\theta + x\cos\theta))}\right]$$

$$\vec{v}_{w}^{NL} = \frac{e^2(\vec{k}_1 - \vec{k}_2)}{2m\omega\omega_1\omega_2}\vec{E}_1..\vec{E}_2{}^* + \frac{e^2}{2m^2\omega c}B_0\cos\theta(\hat{x} + \hat{z}\tan\theta)e^{-ik_0z}$$
$$\times\left[\frac{A_1}{\omega_1}e^{-i(\omega_1 t - k_1(z\sin\theta + x\cos\theta))} + \frac{A_2}{\omega_2}e^{-i(\omega_2 t - k_2(z\sin\theta + x\cos\theta))}\right] \tag{6}$$

The nonlinear current density is

$$\vec{J}_{\omega}^{NL} = -n_o e\vec{v}_{\omega}^{NL}$$

Put the value of $\vec{v}_{\omega}^{NL}$ from equation no. (6)

$$\vec{J}_{\omega}^{NL} = -\frac{n_0e^3(\vec{k}_1 - \vec{k}_2)}{2m\omega\omega_1\omega_2}\vec{E}_1..\vec{E}_2{}^* - \frac{n_0e^3}{2m^2\omega c}B_0\cos\theta(\hat{x} + \hat{z}\tan\theta)e^{-ik_0z}$$
$$\times\left[\frac{A_1}{\omega_1}e^{-i(\omega_1 t - k_1(z\sin\theta + x\cos\theta))} + \frac{A_2}{\omega_2}e^{-i(\omega_2 t - k_2(z\sin\theta + x\cos\theta))}\right] \tag{7}$$

The nonlinear current density lies in the x-z plane: hence, it would excite p-polarized THz wave coupled to space charge wave. Let the self-consistent electric field to this composite wave be.

$$\vec{E}_\omega = \vec{A}(x)e^{-i(\omega t - k_z z)} \tag{8}$$

Where $k_z = k_{1z} - k_{2z}$.

Total force is equal to

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

$$m\frac{\partial \vec{v}}{\partial t} = q\vec{E} + q\vec{v} \times \vec{B}$$

As q= - e for electron so equation becomes

$$\frac{\partial \vec{v}}{\partial t} = -\frac{e\vec{E}}{m} - \frac{-e(\vec{v} \times \vec{B})}{m}$$

Electron experiences a ponder motive force

$$\vec{F} = -e\vec{E}_\omega - \frac{1}{n_0}\nabla(n_\omega T_e)$$

Use $\nabla(n_\omega T_e) = T_e \nabla n_\omega$

$$m\frac{\partial \vec{v}_\omega^{\,L}}{\partial t} = -e\vec{E}_\omega - \frac{1}{n_0}T_e \nabla n_\omega$$

$$\frac{\partial \vec{v}_\omega^{\,L}}{\partial t} = -\frac{e\vec{E}_\omega}{m} - \frac{1}{n_0}\frac{T_e \nabla n_\omega}{m}$$

Put $\frac{T_e}{m} = v_{th}^2$ where v_{th} is the thermal velocity of the electrons.

The self-consistent electric field gives oscillatory velocities to electrons in accordance with the equation of the motion

$$\frac{\partial \vec{v}_{\omega}^{L}}{\partial t} = -\frac{e\vec{E}_{\omega}}{m} - \frac{1}{n_0} v_{th}^2 \nabla n_{\omega} \tag{9}$$

Replace $\frac{\partial}{\partial t} = -i\omega$

$$(-i\omega)\vec{v}_{\omega}^{L} = -\frac{e\vec{E}_{\omega}}{m} - \frac{1}{n_0} v_{th}^2 \nabla n_{\omega}$$

$$\vec{v}_{\omega}^{L} = \frac{e\vec{E}_{\omega}}{mi\omega} + \frac{v_{th}^2}{n_o i\omega} \nabla n_{\omega}$$

Use Poissa’s equation which is $\nabla.\vec{E}_{\omega} = -\frac{n_{\omega} e}{\in_0}$

$$n_{\omega} = -\frac{(\nabla.\vec{E}_{\omega}) \in_0}{e}$$

$$\vec{v}_{\omega}^{L} = \frac{e\vec{E}_{\omega}}{mi\omega} + \frac{v_{th}^2}{n_o i\omega} \nabla \left(-\frac{\nabla.\vec{E}_{\omega}}{e} \right) \in_0$$

$$\vec{v}_{\omega}^{L} = \frac{e\vec{E}_{\omega}}{mi\omega} - \frac{v_{th}^2 \in_0}{n_o i\omega e} \nabla \left(\nabla.\vec{E}_{\omega} \right) \tag{10}$$

The kinetic effects are ignored because the deduction of drift velocity due to the ponderomotive force when $kv_{th} << \omega$, where $k = k_1 - k_2$, $\omega = \omega_1 - \omega_2$

The linear current density is

$$\vec{J}_{\omega}^{L} = -n_0 e \vec{v}_{\omega}^{L}$$

Put the value of $\vec{V}_{\omega}^{L}$ from equation no. (10)

$$\vec{J}_{\omega}^{L} = -\frac{n_0 e^2 \vec{E}_{\omega}}{mi\omega} + \frac{v_{th}^2 \in_0}{i\omega} \nabla(\nabla.\vec{E}_{\omega}) \quad (11)$$

Now by using Maxwell's third & fourth equations, we derive the THz wave equations

The Maxwell's third equation is

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \quad (12)$$

The Maxwell's fourth equation is

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t} \quad (13)$$

Take curl of equation no. (12)

$$\nabla \times (\nabla \times \vec{E}) = -\frac{1}{c}\frac{\partial(\nabla \times \vec{B})}{\partial t}$$

Use Equation no. (13)

$$\nabla \times (\nabla \times \vec{E}) = -\frac{1}{c}\frac{\partial}{\partial t}\left[\frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}\right] \quad (14)$$

Use $\nabla \times (\nabla \times \vec{E}) = \nabla(\nabla.\vec{E}) - \nabla^2 \vec{E}$ in equation no. (14)

$$\nabla(\nabla.\vec{E}) - \nabla^2 \vec{E} = -\frac{1}{c}\frac{\partial}{\partial t}\left[\frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}\right]$$

On rearranging we get

$$\nabla^2 \vec{E} - \nabla(\nabla.\vec{E}) = \frac{4\pi}{c^2}\frac{\partial \vec{J}}{\partial t} + \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}$$

As we know that $\vec{J} = \vec{J}^{L} + \vec{J}^{NL}$ so our equation becomes.

$$\nabla^2 \vec{E} - \nabla(\nabla.\vec{E}) = \frac{4\pi}{c^2}\left[\frac{\partial \vec{J}^L}{\partial t} + \frac{\partial \vec{J}_{NL}}{\partial t}\right] + \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}$$

The above equation is the general equation which is derived from Maxwell's third and fourth equation.

For THz wave, the above equation becomes

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{4\pi}{c^2}\left[\frac{\partial \vec{J}_\omega^L}{\partial t} + \frac{\partial \vec{J}_\omega^{NL}}{\partial t}\right] + \frac{1}{c^2}\frac{\partial^2 \vec{E}_\omega}{\partial t^2} \qquad (15)$$

Use the value of $\vec{J}_\omega^L$ from equation no. (11)

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{4\pi}{c^2}\left[\frac{\partial}{\partial t}\left(\frac{-n_0 e^2}{mi\omega}\vec{E}_\omega\right) + \frac{\partial}{\partial t}\left(\frac{v_{th}^2 \in_0}{i\omega}\right)\nabla(\nabla.\vec{E}_\omega) + \frac{\partial \vec{J}_\omega^{NL}}{\partial t}\right] + \frac{1}{c^2}\frac{\partial^2 \vec{E}_\omega}{\partial t^2}$$

Replace $\frac{\partial}{\partial t}$ by $(-i\omega)$

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{4\pi}{c^2}\left[(-i\omega)\left(\frac{-n_0 e^2}{mi\omega}\vec{E}_\omega\right) + (-i\omega)\left(\frac{v_{th}^2 \in_0}{i\omega}\right)\nabla(\nabla.\vec{E}_\omega) + (-i\omega)\vec{J}_\omega^{NL}\right] + \frac{1}{c^2}(i^2\omega^2)\vec{E}_\omega$$

After simplification we get

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{4\pi n_0 e^2}{mc^2}\vec{E}_\omega - \frac{4\pi}{c^2}v_{th}^2 \in_0 \nabla(\nabla.\vec{E}_\omega) + \frac{4\pi}{c^2}(-i\omega)\vec{J}_\omega^{NL} - \frac{1}{c^2}\omega^2\vec{E}_\omega$$

Put $\frac{4\pi n_0 e^2}{m} = \omega_p^2$ in c.g.s.

where w_p is the frequency of plasma

After solving we get

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{\omega_p^2}{c^2}\vec{E}_\omega - \frac{4\pi}{c^2} v_{th}^2 \in_0 \nabla(\nabla.\vec{E}_\omega) - \frac{4\pi}{c^2} i\omega \vec{J}_\omega^{NL} - \frac{1}{c^2}\omega^2 \vec{E}_\omega$$

After rearranging all terms, we get

$$\nabla^2 \vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) + \frac{4\pi}{c^2} v_{th}^2 \in_0 \nabla(\nabla.\vec{E}_\omega) + \frac{\omega^2}{c^2}\vec{E}_\omega - \frac{\omega_p^2}{c^2}\vec{E}_\omega = -\frac{4\pi}{c^2} i\omega \vec{J}_\omega^{NL}$$

$$\nabla^2 \vec{E}_\omega - \left(1 - \frac{4\pi}{c^2} v_{th}^2 \in_0\right)\nabla(\nabla.\vec{E}_\omega) + \left(\frac{\omega^2 - \omega_p^2}{c^2}\right)\vec{E}_\omega = -\frac{4\pi}{c^2} i\omega \vec{J}_\omega^{NL} \tag{16}$$

In the absence of nonlinear source, this equation offers two distinct solutions: one an electromagnetic wave (with $\nabla.\vec{E} = o$)

$$\vec{E}_m = A_m (\hat{x} - \frac{k_{mx}}{k_z}\hat{z}) e^{+ik_{mx}} e^{-i(\omega t - k_z z)} \tag{17}$$

And other a Langmuir wave (with $\nabla \times \vec{E} = o$).

$$\vec{E}_s = A_s (\hat{x} + \frac{k_z}{k_{sx}}\hat{z}) e^{+ik_{mx}} e^{-i(\omega t - k_z z)} \quad - \tag{18}$$

Where $k_{mx} = (\omega^2 - \omega_p^2 - k_z^2 c^2)^{1/2} / c$, $k_{sx} = (\omega^2 - \omega_p^2 - k_z^2 {v_{th}}^2)^{1/2} / v_{th}$. (19)

In this deduction, isothermal approximation is implicit for the electron response. By suitably multiplying the electron temperature by the ratio of specific heats at constant pressure and constant volume, one can have it valid in the adiabatic approximation.

With the nonlinear current source, the particular solution, recognizing that $\vec{J}_w^{NL} \| \vec{k} \| (\vec{k}_1 - \vec{k}_2)$

and varies as $e^{-i(\omega t-\vec{k}.\vec{r})}$, can be written as

$$\vec{E}_p = -\frac{i\omega\vec{J}_\omega^{NL}}{\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2)} \tag{20}$$

Since $\nabla\times\vec{E}_s = o$, $\nabla\times\vec{E}_p = o$,there is no magnetic field associated with $\vec{E}_s$, $\vec{E}_p$. The magnetic field associated with $\vec{E}_m$ is

$$\vec{H}_m = \frac{\vec{k}_m\times\vec{E}_m}{\mu_0\omega} \tag{21}$$

Put $\vec{k}_m = k_{mx}\hat{x}+k_z\hat{z}$ and take the value of $\vec{E}_m$ from equation no. (17)

$$\vec{E}_m = A_m(\hat{x}-\frac{k_{mx}}{k_z}\hat{z})e^{+ik_x}e^{-i(\omega t-k_z z)}$$

So equation (21) becomes

$$\vec{H}_m = \frac{(k_{mx}\hat{x}+k_z\hat{z})}{\mu_0\omega}\times A_m(\hat{x}-\frac{k_{mx}}{k_z}\hat{z})e^{ik_{mx}x}e^{-i(\omega t-k_z z)}$$

$$\vec{H}_m = \frac{(k_{mx}\hat{x}+k_z\hat{z})\times A_m(k_z\hat{x}-k_{mx}\hat{z})}{\mu_0\omega k_z}e^{ik_{mx}x}e^{-i(\omega t-k_z z)}$$

As $\hat{x}\times\hat{x}=0$

$$\vec{H}_m = \frac{-k_{mx}^2(-\hat{y})+k_z^2(\hat{y})}{\mu_0\omega k_z}A_m e^{ik_{mx}x}e^{-i(\omega t-k_z z)}$$

$$\vec{H}_m = \frac{(k_z^2 + k_{mx}^2)}{\mu_0 \omega k_z} \hat{y} A_m e^{+ik_{mx}x} e^{-i(\omega t - k_z z)} \tag{22}$$

In the vacuum region (x < 0) there exists only outgoing electromagnetic wave (THz) with

$$\vec{E}_R = A_R (\hat{x} + \frac{k_x}{k_z} \hat{z}) e^{-ik_x x} e^{-i(\omega t - k_z z)} \tag{23}$$

$$\vec{H}_R = \frac{\vec{k}_R \times \vec{E}_R}{\mu_0 \omega}$$

Put $\vec{k}_R = -k_x \hat{x} + k_z \hat{z}$ (as we are talking about region x< 0) and take the value of $\vec{E}_R$ from equation no. (22)

$$\vec{H}_R = \frac{(-k_x \hat{x} + k_z \hat{z}) \times A_R (k_Z \hat{x} + k_x \hat{z})}{\mu_0 \omega k_z} e^{-ik_x x} e^{-i(\omega t - k_z z)}$$

As $\hat{x} \times \hat{x} = 0$

$$\vec{H}_R = \frac{-k_x^2 (-\hat{y}) + k_z^2 \hat{y}}{\mu_0 \omega k_z} A_R e^{-ik_x x} e^{-i(\omega t - k_z z)}$$

$$\vec{H}_R = \frac{(k_z^2 + k_x^2)}{\mu_0 \omega k_z} \hat{y} A_R e^{-ik_x x} e^{-i(\omega t - k_z z)} \tag{24}$$

Where $k_x = \frac{\omega \cos \theta}{c}$ & $k_z = \frac{\omega \sin \theta}{c}$ (25)

The first boundary condition is

At x=o E_Z must be continuous.

The second boundary condition is

At x=0 H_y must be continuous.

Now deduce the third boundary condition from equation no.

Taking z component of equation no. (16)

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)E_{\omega z}-\left(1-\frac{4\pi}{c^2}v_{th}^2\in_0\right)\left[\frac{\partial}{\partial z}\left(\frac{\partial E_{\omega x}}{\partial x}\right)+\frac{\partial^2 E_{\omega z}}{\partial z^2}\right]+\left(\frac{\omega^2-\omega_p^2}{c^2}\right)E_{\omega z}=-\frac{4\pi}{c^2}i\omega J_{\omega z}^{NL}$$

Replacing $\frac{\partial}{\partial Z}$ by ik_z then equation becomes

$$\left(\frac{\partial^2}{\partial x^2}+(i^2k_z^2)\right)E_{\omega z}-\left(1-\frac{4\pi}{c^2}v_{th}^2\in_0\right)\left[(ik_z)\left(\frac{\partial E_{\omega x}}{\partial x}\right)+(i^2k_z^2)\right]+\left(\frac{\omega^2-\omega_p^2}{c^2}\right)E_{wz}=-\frac{4\pi}{c^2}i\omega J_{wz}^{NL}$$

$$\frac{\partial^2 E_{\omega z}}{\partial x^2}-k_z^2E_{\omega z}-ik_z\left(1-\frac{4\pi}{c^2}v_{th}^2\in_0\right)\frac{\partial E_{\omega x}}{\partial x}+k_z^z\left(1-\frac{4\pi}{c^2}v_{th}^2\in_0\right)+\left(\frac{\omega^2-\omega_p^2}{c^2}\right)E_{wz}=-\frac{4\pi}{c^2}i\omega J_{wz}^{NL}$$

Integrate it over x from 0^- (reflected wave) to 0^+ (incident wave) & neglected those terms which have no dependence on x

$$\left.\frac{\partial E_{\omega z}}{\partial x}\right|_{0^-}^{0^+}-ik_z\left(1-4\pi\varepsilon_0\frac{v_{th}^2}{c^2}\right)E_{\omega x}\Big|_{0^-}^{0^+}=0$$

For 0^- case means for reflected part $v_{th}=0$ because we are in region x< 0 & in this region no electrons are there. So thermal velocity due to electrons is 0. So above equation becomes

$$\left(\frac{\partial E_z}{\partial x}-ik_z\left(1-4\pi\varepsilon_0\frac{v_{th}^2}{c^2}\right)E_x\right)_{0^+}=\left(\frac{\partial E_{\omega z}}{\partial x}-ik_zE_{\omega x}\right)_{0^-} \qquad (26)$$

This is the third boundary condition.

Now apply first boundary condition

i.e. at x=0 E_z must be continuous.

$$E_{mz} + E_{sz} + E_{pz} = E_{Rz} \tag{27}$$

From equation no (17) write the z component of E_m at x=0

$$E_{mz} = -A_m \frac{k_{sx}}{k_z} e^{-i(\omega t - k_z z)}$$

From equation no (18) write the z component of E_s at x=0

$$E_{sz} = A_s \frac{k_z}{k_{sx}} e^{-i(\omega t - k_z z)}$$

From equation no (20) write the z component of E_p at x=0

$$E_{pz} = -\frac{-i\omega \vec{J}_{wz}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k_z^2 v_{th}^2)}$$

From equation no (23) Write the z component of E_R at x=0

$$E_{Rz} = A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)}$$

Use all these values of E_{mz}, E_{sz}, E_{pz} & E_{Rz} in equation no. (27) We get

$$-\frac{k_{mx}}{k_z} A_m e^{-i(\omega t - k_z z)} + \frac{k_z}{k_{sx}} A_s e^{-i(\omega t - k_z z)} - \frac{i\omega J_{wz}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)} = \frac{k_x}{k_z} A_R \tag{28}$$

Apply second boundary condition

i.e. H_y must be continuous at x=0

Means $H_{mz} = H_{Rz}$ (29)

From equation no. (22) Write the y component of H_m at x=0

$$H_{mz} = \frac{k_{mx}^2 + k_z^2}{\mu_0 \omega k_z} A_m e^{-i(\omega t - k_z z)}$$

From equation no. (24) Write the y component of H_R at x=0

$$H_{Rz} = \frac{k_x^2 + k_z^2}{\mu_0 \omega k_z} A_R e^{-i(\omega t - k_z z)}$$

Use these values of H_{mz} & H_{Rz} in equation no. (29)

$$\frac{k_{mx}^2 + k_z^2}{\mu_0 \omega k_z} A_m = \frac{k_x^2 + k_z^2}{\mu_0 \omega k_z} A_R$$

$$A_m = \frac{k_x^2 + k_z^2}{k_{mx}^2 + k_z^2} A_R \tag{30}$$

Now apply third boundary condition

In equation no. (26) L.H.S. is for incident wave

$$E_z = E_{mz} + E_{sz} + E_{pz} \tag{31}$$

$$E_x = E_{mx} + E_{sx} + E_{pz} \tag{32}$$

To solve L.H.S. for eqn. (26) we find E_z

To find E_z write the z component of E_m from equation no. (17)

$$E_{mz} = -A_m \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)}$$

Write the z component of E_s from equation no. (18)

$$E_{sz} = A_s \frac{k_z}{k_{sx}} e^{-i(\omega t - k_z z)}$$

Write the z component of E_p from equation no. (20)

$$E_{pz} = -\frac{-i\omega J_{\omega z}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)}$$

Use all these values in equation no.(31)we get

$$E_z = -A_m \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)} + A_s \frac{k_z}{k_{sx}} e^{-i(\omega t - k_z z)} - \frac{-i\omega J_{wz}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)} \tag{33}$$

Similarly we find E_x

To find E_x write the x component of E_m from equation no. (17)

$$E_{mx} = A_m e^{-i(\omega t - k_z z)}$$

Write the x component of E_s from equation no. (18)

$$E_{sx} = A_s e^{-i(\omega t - k_z z)}$$

Write the z component of E_p from equation no.(20)

$$E_{pz} = -\frac{-i\omega J_{\omega z}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)}$$

Use all these values in equation no. (32)

$$E_x = A_m e^{-i(\omega t - k_z z)} + A_s e^{-i(\omega t - k_z z)} - \frac{-i\omega J_{\omega z}^{NL}}{\in_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)} \tag{34}$$

Take partial derivative of equation (33) w.r.t. x

$$\frac{\partial E_z}{\partial x} = \frac{\partial}{\partial x}\left(-A_m \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)} \right) + \frac{\partial}{\partial x}\left(A_s \frac{k_z}{k_{sx}} e^{-i(\omega t - k_z z)} \right) + \frac{\partial}{\partial x}\left(-i\omega \frac{J_{wz}^{NL}}{\varepsilon_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2}\right)$$

$$\frac{\partial E_z}{\partial x} = (ik_{mx})\left(-A_m \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)} \right) + (ik_{sx})\left(A_s \frac{k_z}{k_{sx}} e^{-i(\omega t - k_z z)} \right) - i\omega \frac{\partial}{\partial x}\left(\frac{J_{wz}^{NL}}{\varepsilon_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2}\right) \tag{35}$$

In equation no (26) R.H.S if for reflected wave

$$E_{\omega z} = E_{Rz} \tag{36}$$

$$E_{\omega x} = E_{Rx} \tag{37}$$

To solve equation (36) write the z component of E_R from equation no. (23)

$$E_{Rz} = A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)}$$

The equation no (36) becomes

$$E_{\omega z} = A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)} \tag{38}$$

To solve equation (37) write the x component of E_R from equation no (23)

$$E_{Rx} = A_R e^{-i(\omega t - k_z z)}$$

The equation no (37) becomes

$$E_{\omega x} = A_R e^{-i(\omega t - k_z z)} \tag{39}$$

Take the partial derivative of equation (38)

$$\frac{\partial E_{\omega z}}{\partial x} = \frac{\partial}{\partial x}\left(A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)} \right)$$

$$\frac{\partial E_{\omega z}}{\partial x} = (-ik_x)\left(A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)} \right)$$

$$\frac{\partial E_{\omega z}}{\partial x} = -iA_R \frac{k_x^2}{k_z} e^{-i(\omega t - k_z z)} \tag{40}$$

Use the value of equation no (34),(35),(39),(40) in equation no (26),then we obtain

$$-iA_m \frac{k_{mx}^2}{k_z} e^{-i(\omega t - k_z z)} + iA_s k_z e^{-i(\omega t - k_z z)} - i\omega \frac{\partial}{\partial x} \frac{J_{\omega z}^{NL}}{\varepsilon_0(\omega^2 - \omega_p^2 - k^2 v_{th}^2 \_)} - ik_z \left(1 - 4\pi\varepsilon_0 \frac{v_{th}^2}{c^2} \right)$$

$$\left[A_m e^{-i(\omega t - k_z z)} + A_s e^{-i(\omega t - k_z z)} - i\omega \frac{J_{\omega z}^{NL}}{\varepsilon_0(\omega^2 - \omega_p^2 - k^2 v_{th}^2)} \right] = -iA_R \frac{k_x^2}{k_z} e^{-i(\omega t - k_z z)} - iA_R k_z e^{-i(\omega t - k_z z)}$$

Replace $\frac{\partial}{\partial x}$ by ik_x in above equation because

$$\frac{\partial}{\partial x}=i(k_1-k_2)\cos\theta=ik\cos\theta=ik_x$$

The above equation becomes

$$-A_m\frac{k_{mx}^2}{k_z}e^{-i(\omega t-k_z z)}+A_s k_z e^{-i(\omega t-k_z z)}-\frac{i\omega k_x J_{\omega z}^{NL}}{\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2\_)}-k_z\left(1-4\pi\varepsilon_0\frac{v_{th}^2}{c^2}\right)$$
$$\left[A_m e^{-i(\omega t-k_z z)}+A_s e^{-i(\omega t-k_z z)}-i\omega\frac{J_{\omega z}^{NL}k_x/k_z}{\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2)}\right]=-A_R\frac{k_x^2}{k_z}e^{-i(\omega t-k_z z)}-A_R k_z e^{-i(\omega t-k_z z)}$$

$$A_m k_{mx}^2 e^{-i(\omega t-k_z z)}-A_s k_z^2 e^{-i(\omega t-k_z z)}+\frac{i\omega k_x k_z J_{\omega z}^{NL}}{\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2\_)}+\left(k_z^2-4\pi\varepsilon_0 k_z^2\frac{v_{th}^2}{c^2}\right)$$
$$\left[A_m e^{-i(\omega t-k_z z)}+A_s e^{-i(\omega t-k_z z)}-i\omega\frac{J_{\omega z}^{NL}k_x/k_z}{\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2)}\right]=A_R(k_x^2+k_z^2)e^{-i(\omega t-k_z z)}$$

$$\left[k_{mx}^2+k_z^2\left(1-4\pi\varepsilon_0\frac{v_{th}^2}{c^2}\right)\right]A_m e^{-i(\omega t-k_z z)}-4\pi\varepsilon_0 k_z^2\left(\frac{v_{th}^2}{c^2}\right)A_s e^{-i(\omega t-k_z z)}+\frac{4\pi i\omega k_x k_z v_{th}^2 J_{\omega z}^{NL}}{c^2(\omega^2-\omega_p^2-k^2v_{th}^2)}$$
$$=A_R(k_x^2+k_z^2)e^{-i(\omega t-k_z z)}$$

(41)

From equation (28)

$$A_s = \frac{k_{sx}}{k_x} e^{-i(\omega t - k_z z)} \left[A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)} + A_m \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)} + \frac{i\omega J_{\omega z}^{NL}}{\varepsilon_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)} \right]$$

(42)

Use equation (42) (30) in (41)

$$\left[k_{mx}^2 + k_z^2 \left(1 - 4\pi\varepsilon_0 \frac{v_{th}^2}{c^2} \right) \right] \left(\frac{k_x^2 + k_z^2}{k_{mx}^2 + k_z^2} \right) A_R e^{-i(\omega t - k_z z)} - 4\pi\varepsilon_0 k_z^2 \left(\frac{v_{th}^2}{c^2} \right) e^{-i(\omega t - k_z z)} \frac{k_{sx}}{k_z} e^{-i(\omega t - k_z z)}$$

$$\left[A_R \frac{k_x}{k_z} e^{-i(\omega t - k_z z)} + \left(\frac{k_x^2 + k_z^2}{k_{mx}^2 + k_z^2} \right) A_R \frac{k_{mx}}{k_z} e^{-i(\omega t - k_z z)} + \frac{i\omega J_{\omega z}^{NL}}{\varepsilon_0 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)} \right] + \frac{4\pi i\omega k_x k_z v_{th}^2 J_{\omega z}^{NL}}{c^2 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)}$$

$$= A_R (k_x^2 + k_z^2) e^{-i(\omega t - k_z z)}$$

(43)

Use the value of k_{mx} from equation (19) we get

$$k_{mx}^2 + k_z^2 = \frac{\omega^2 - \omega_p^2}{c^2} \qquad (44)$$

Use equation (44) in (43)

$$\left[\frac{(k_x^2 + k_z^2)(k_z^2 + k_{mx} k_{sx})}{\omega^2 - \omega_p^2} + \frac{k_{sx} k_x}{c^2} \right] A_R e^{-i(\omega t - k_z z)} = \frac{-i\omega J_{\omega z}^{NL} k_z k_x \left(1 + \frac{k_{sx}}{k_x} \right)}{\varepsilon_0 c^2 (\omega^2 - \omega_p^2 - k^2 v_{th}^2)}$$

Use the value of k_x and k_z from equation no (25) the above equation becomes

$$\left[\frac{\omega^2}{c^2}\frac{(k_z^2+k_{mx}k_{sx})}{\omega^2-\omega_p^2}+\frac{k_{sx}k_x}{c^2}\right]A_R e^{-i(\omega t-k_z z)}=\frac{-i\omega J_{\omega z}^{NL}k_z k_x\left(1+\frac{k_{sx}}{k_x}\right)}{\varepsilon_0 c^2(\omega^2-\omega_p^2 \_ k^2 v_{th}^2)}$$

After solving we get

$$A_R e^{-i(\omega t-k_z z)}=\frac{-i\omega k_x k_z J_{\omega z}^{nl}\left(1+\frac{k_{sx}}{k_x}\right)}{c^2k^2\varepsilon_0(\omega^2-\omega_p^2-k^2v_{th}^2)\left[\frac{k_z^2+k_{mx}k_{sx}}{\omega^2-\omega_p^2}+\frac{k_x k_{sx}}{\omega^2}\right]} \tag{45}$$

CHAPTER-4

RESULTS AND DISCUSSION

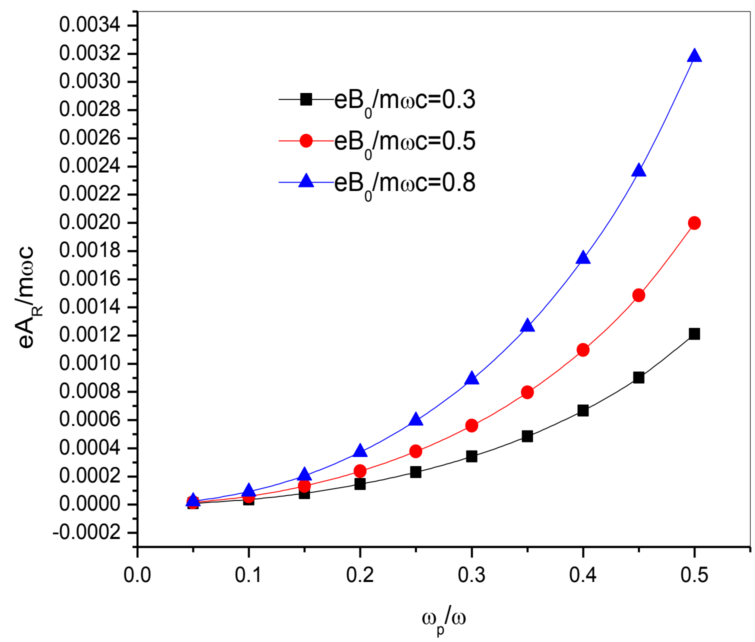

Fig 1: Variation of normalized amplitude of the THz wave ($eA_R / m\omega c$) with the normalized plasma frequency for different values of applied wiggler magnetic field $eB_0 / m\omega c$ =0.3, 0.5 &0.8

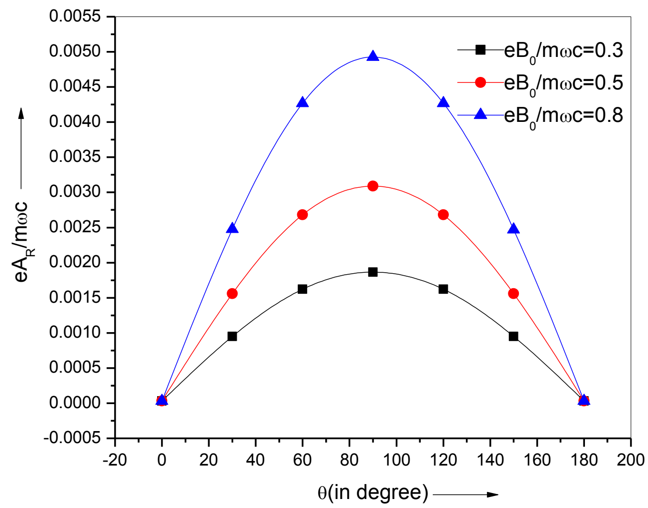

Fig 2: Variation of normalized amplitude of the THz reflected wave ($eA_R/m\omega c$) with the angle of incidence for different values of applied wiggler magnetic field $eB_0/m\omega c$ =0.3, 0.5&0.8

We have solved the equation (45) for the following parameters $\frac{\omega}{\omega_p}$= 1.4; $\frac{ck_z}{\omega_p}$=0.9; $\frac{ck_x}{\omega_p}$ =1.1; $\frac{k_{sx}}{k_x}$=1; $\frac{eA_1}{m\omega_1 c}$=0.05; $\frac{eA_2^*}{m\omega_2 c}$=0.05; k_z=0.1; $\frac{eB_0}{m\omega c}$=0.3, 0.5, 0.8; $\frac{\omega_0}{\omega_p}$=0.6; $\frac{\omega_1}{\omega_p}$=1.5; $\frac{eA_2}{m\omega_2 c}$=0.05; $\frac{\omega_2}{\omega_p}$=1.4; $\frac{kv_{th}}{\omega_p}$=0.7; $\frac{ck_{mx}}{\omega_p}$=0.38; $\frac{k_{sx}v_{th}}{\omega_p}$=1; $\frac{c}{v_{th}}$=10

Fig. 1 depicts the variation of normalized amplitude of the reflected THz wave $eA_R/m\omega c$ as a function of normalized frequency of the plasma wave ω_p/ω for different values of the applied wiggler magnetic field $eB_0/m\omega c$ =0.3, 0.5 & 0.8. The amplitude of the reflected THz wave increases as we increase the value of the normalized plasma frequency. It is also clear from Fig.1 that as we increases the magnetic field the amplitude of the THz wave enhances. In Fig. 2 we have plotted normalized amplitude of the reflected THz wave $eA_R/m\omega c$ as a function of the incidence angle θ (in degree) for different values of the applied wiggler magnetic field

$eB_0 / m\omega c$ =0.3,0.5&0.8.The amplitude of the reflected THz wave increases as we increase the angle of the incidence. It is also clear from Fig.2 that as we increases the value of the magnetic field the amplitude of the THz wave enhances. We have also optimized the value of angle of incidence, wiggler magnetic field and laser parameters.

Optimized value of laser and plasma parameter would be useful in order to enhance the efficiency of THz radiations.

CHAPTER-5

CONCLUSION

THz radiation during laser plasma interaction in the presence of wiggler magnetic field has been investigated. THz generation in plasma is significantly influenced by the presence of wiggler magnetic field. We have optimized laser and plasma parameter in order to produce efficient terahertz radiations. The effect of increasing plasma density increases the normalized terahertz amplitude. The angle of incidence of laser beams into the plasma plays a vital role in the enhancement of THz radiations. Our results would be useful for the scientists who are working in the field of THz radiation generation.

CHAPTER-6

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